FRACTURE CONTROL OF SPACE FLIGHT STRUCTURES AND PRESSURE VESSELS

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ABSTRACT

The fracture control requirements and their implementation for the design and operation of NASA and Airforce spaceflight hardware are reviewed in this paper. The paper till focus on two categories of spaceflight hardware: (1) Space Shuttle payloads which include significant portions of the international space station under development and (2) flight pressure vessels. The NASA and Airforce have developed detailed fracture control requirements for space shuttle payloads and pressure vessels and these will be discussed in this paper, The paper will also discuss the lessons learned in incorporating the fracture control requirements in space flight hardware especially in the Space Shuttle program.

INTRODUCTION

Fracture control is the application of design philosophy, analysis method, manufacturing technology, quality assurance, and operating procedures to prevent premature failure of hardware due to the propagation of undetected cracks or crack-like defects (flaws) during fabrication, testing, transportation and handling, and service. Fracture control has been formally implemented in the space programs beginning in 1970. NASA-SP-8040 [11 was the first document to specify the fracture control requirements for space flight hardware and it was for pressure vessels in space flight systems. In 1972, the Air Force completed its development of a requirements document, the MIL-ST[) 1522, for the design of pressurized space and missile systems. lhis document was revised in 19B4 to become MIL-STD 1527A [21. At present MIL-STD 1522A is accepted as the primary requirements document for space flight vessels.

Although fracture control methodology was being used in other industries such as commercial and military aviation and the nuclear power industry, the Space Shuttle was the first space program to incorporate a comprehensive fracture control plan 131 for its design, development, and operation, There was no precedent for such usage on a space system since it was a reusable tinged vehicle designed for 100 launches and landings [41. After the Challenger mishap, NASA went through an extensive safety reviewofthe Space Shuttle and its operations. One outcome of this review was that NASA developed a central fracture control document, NHB 8071. I [5], for payloads and associated hardware to be flown on the Space Shuttle. At present NHB 8071.1 is the accepted requirements document for all payloads flown in Space Shuttle which include some key elements of the Space Station which are to be assembled in space around the turn of this century.

PAYLOAD REQUIREMENTS

For a flight payload system to be flown in the Space Shuttle, the design and use of each of its hardware components must be reviewed to determine whether a pre-existing crack in the component may lead to a catastrophic hazard. A catastrophic hazard is defined as an event which can disable or cause fatal personnel injury or loss of the Space Shuttle Examples of such events include a failure and a subsequent release from a payload any part or fragment having mass and or energy that can potentially punch through the wdll of the cargo bay, a release of a significant amount of hazardous substance into the cargo bay, or a failure that prevents closure of the cargo-bay door. The payloads requirements document NHB 8071.1 contains the procedures for fracture control classification of all payload components as shown in the flowchart in Figure 1.

Non-Fracture Critical Categories

Components classified as exempt parts, low-released-mass parts, contained parts and fail-safe parts are not fracture critical. They can be processed under conventional aerospace industry verification and quality assurance requirements. *Exempt* components are those that are clearly non-structural and not susceptible to failure as a result of crack propagation. Components that may be included in exempt category are insulation blankets, tire bundles, and elastomeric seals, The total released mass, the fracture toughness of the part material, and if the part is preloaded in tension will determine whether a component may be categorized as a *low-released-mass* part. A preloaded, low fracture toughness component with a mass less than 13.6 grams (0.03 lbs) whose failure will not result in the release of a larger part may be classified as a non-fracture critical part. However, this mass may be as high as 113.5 grams (0.25 lbs) if the part is not preloaded and is made of high fracture toughness material. A payload component may be classified as a *contained* part if its failure and subsequently the failure of its container does not result in the release of elements with a combined mass exceeding the low-release-mass limit. The containment capability may be assessed by test or analysis. An empirical approach that is often used calculates the required thickness of the container by equating the kinetic energy of the released fragment to an estimate of the work required to punch out a hole from the container wall. The final *fail-safe* category in general applies only to redundant structural designs that are not classified as pressure vessels or high energy rotating equipment. In addition to being deemed redundant a fail-safe design should ensure that fragments from a failed structural element does not exceed the low-release-mass limit. An example of a fail safe component may be an electronic box attached with multiple fasteners,

Fracture Critical Components

All the parts that cannot be classified as non-fracture-critical are deemed fracture-critical parts. Fracture critical components should have their damage tolerance arid/or safe-life verifred by either test or analysis. The safe fife analysis should be performed based on the state-of-the-art fracture mechanics principles. Apart satisfies safe-life criteria when nondestructive evaluation (NDE) is perforrned to screen out crack above a particular size and then show by analysis or test that an assumed crack of that size will not grow to failure when subjected to the cyclic and sustained loads encountered during four complete service lifetimes. The selection of NDE methods and level of inspection should be based on fracture mechanics analysis and the safe-life acceptance requirements of a specific part. The minimum initial crack sizes for safe-life analysis using different NDE methods are shown in Table 1, Proof testis sometimes used to establish a crack size for safe life analysis.

One complete service lifetime includes all significant loading events that occur after NDE-. Software codes with proven methodology and reliable material database such as NASA/FLAGRO [6] should be used to per furm the required safe-fife analyses. Crack growth analysis of composite materials is beyond the current state -of-tile-art The fracture control requirement for composite structures is satisfied by proof testing it to 1.2 times the limit load and through NDE. NHB 8071.1 also allows for an approach to keep the limit load strains below a threshold strain level at which the composite is damage tolerant.

PRESSURE VESSEL REQUIREMENTS

All space-flight pressure vessels are designated as fracture critical. MIL-STD-1522A offers three approaches, namely A, B, and C as shown in Figure 2, for design analysis and verification of pressure vessels. Approach B, the strength of materials approach, is not acceptable by both USAF/SD and NASA since it assumes that no flaws are present in the vessel and Approach C, the approach complying with the ASME pressure vessel code, is seldom used for flight vessel development since it results in an overweight vessel.

Thus, Approach A is the only one applicable for flight vessels. Two paths may be followed in this approach based on whether the failure mode is (1) LBB with non-hazardous contents, or (2) Brittle (Non-LBB) or LBB with hazardous contents. The LBB failure mode maybe demonstrated by analysis or test by showing that an initial flaw shape (given by ratio of crack depth a to half length c) in the range $.05 \le a/c \le 0.5$ will propagate through the thickness of the pressure vessel before becoming critical. An appendix contained in MIL-STD 1522 provides an acceptable approach for failure mode determination. A pressure vessel is considered to exhibit a ductile fracture mode (LBB) when

$$\frac{K_{Ic}}{\sigma_{op}} \geq 2\alpha\sqrt{t} \qquad (\alpha\sigma_{op} \leq \sigma_{ys},\ \alpha > 1)$$

where K_{Ic} is the plane strain fracture toughness of tdnk material, σ_{op} is the operating stress *level*, α is the proof test factor, t is the wall thickness, and σ_{ys} is the yield strength of tank material,

For Path (1) in Approach A, no further fracture mechanics analysis is required when the Miner's rule is satisfied by a fatigue analysis of the unflawed vessel. Qualification testing of the vessel requires an LBB demonstration (waived if shown analytically), pressure testing, and random vibration testing. Pressure testing requires that there be no yield after pressure cycling for either (i) 2 x number of operating cycles at 1.5 x mean expected operating pressure (MEOP), or (ii) 4 x number of operating cycles at 1.0 x MEOP, and there be no burst when pressurized to burst factor (B.F.) x ME OP. Acceptance tests conducted on each pressure vessel before commitment to flight require an NDI and a proof pressure test. The proof test is intended to detect any errors in the manufacturing processor workmanship and in the specification of the materials. Most flight pressure vessels are designed to a B.F. of 1.5.

For Path (7) in Approach A, a safe-life analyses (or tests) of the vessel is required with a pre-existing initial flaws to showthat life is greater than four times the service life of the vessel. Safe-life of the vessel is the period during which it is predicted not to fail in the expected operating environment. The requirements for qualifying the vessels by pressure testing and random vibration are the same as for Patti (1) above. However, the acceptance tests in this case would be required to establish the initial flaw size used in the safe-life analysis in addition to detecting any errors in the manufacturing.

Non-composite vessels anti composite vessels with metallic liners satisfy the same requirements with a few exceptions. However, composite vessels without a load carrying metallic liner may only be designed by the ASME pressure vessel code, Section X. The LBB failure mode determination for the metal lined vessel is only based on the liner, and fracture mechanics methodology is not applicable to the composite overwrap. Conventional fatigue life analysis of the composite overwrap must verify that the liner is the critical safe-life component by shoving that the life of the overwrap is at least ten times longer than that of the liner

The section on pressurized systems contains general requirements for system design featores, including routing of piping and tubing, physical separation of components, electrical grounding, anti safety of ground handling, tooling, and testing. It also includes pressure relief requirements related to locations of pressure relief devices, flowcapacity, sizing, venting, filtering, and negative pressure protection. Design requirements for control devices and detail requirements specific to hydraulic and pneumatic systems are also contained in this section.

Some modifications and exceptions to the MIL-S11) 1522A are specified in NASA fracture control requirements document for Space Shuttle Payloads, NHB 8071.1 [51. For analytical I BB demonstration, a crack growth analysis is preferred to using the ductile fracture equation given in the 1522A appendix. 10 accommodate the use of one-o f-a kind vessels, the NASA documents 8071.1 and 1700.7 allow a proof test at a minimum of 1.5 x MDP and a fatigue analysis showing a minimum of ten design lifetimes in lieu of the burst and fatigue life tests required by 1522A. NASA requires an additional NDI of the welds in the pressore vessels shell after proof testing to screen the initial NDI flaw size assumed for analysis.

For a composite pressure vessel with a metal liner, an additional NASA requirement is to demonstrate damage tolerance of the overwrap Damage tolerance is the ability of the pressure vessel to resist failure doe to the presence of flaws for specified period of unrepaired usage. Unlike for the metallic liner, linear elastic fracture mechanics is not strictly valid for the composite overwrap. Thus, fracture control of the overwrap till be based on the use of NDI and manufacturing process control.

Recently, the MIL-STD-1522A has been updated by I he Aerospace Corporation. A draft copy of the updated standard which specifies the safe-life demonstration requirement for pressurized structures containing hazardous fluids such as launch vehicle main propellant tanks has been reviewed by government agencies and aerospace industries. This updated military standard in being converted into an industry standard which consists of two volumes. Volume I [7] covers metallic pressure vessels(spacecraft liquid propellant storage tanks and high pressure gas bottles), pressurized structures (launch vehicle main propellant tanks), special pressurized equipment (batteries, heat pipes, cryostats and sealed container) and pressure components (lines, fittings, valves and hose). The requirements for composite hardware including composite overwrapped pressure vessels will be covered in Volume II- Composite Hardware.

LESSONS LEARNED

The most important aspect of cost effectively implementing fracture control for flight hardware is to prepare a safety verification plan which incorporates the relevant fracture *control* requirements early in the program. It is important to make the designers and analysts also aware of the requirements and damage tolerant design approaches at the onset since most structural parts can be designed tolerant of initial flaw without significantly complicating the design or adding much cost. Every effort should be made to design the components of space hardware so that they fall into one of the non-fracture critical categories described above. However the fracture critical category cannot be avoided for components such as pressure vessels and those having high-energy rotating parts, and parts which need to be made with brittle materials, welded joints, composite materials, or bonded joints.

Despite having four available non-fracture critical categories, implementing the requirements for certain Space Shuttle payloads resulted in extensive fracture critical parts lists. However, most of these parts either carried very small loads, or made of highly ductile material and were made with processes in which initial cracks are extremely unlikely. An outcome of this was the creation of yet another oon-fracture critical category called low risk parts in the revised NHB 8071.1 document. Low risk parts must be made from metal highly resistant to fracture with well established processes and demonstrate low probabilities of crack presence and growth.

As mentioned above the Space Shuttle was the first space program to incorporate a comprehensive approach to prevent structural failures resulting from cracks or crack-like defects. Fracture control plans were devel- oped for the orbiter, solid rocket booster, main engine, and external tank. It was planned to produce five flight vehicles, and orbiter test verification for safe life would have been relatively costly (in terms of total program costs) compared to similar verification tests for commercial and military aircrafts programs. Hence fracture control requirements were met for the Shuttle program by a mixture of analysis and test.

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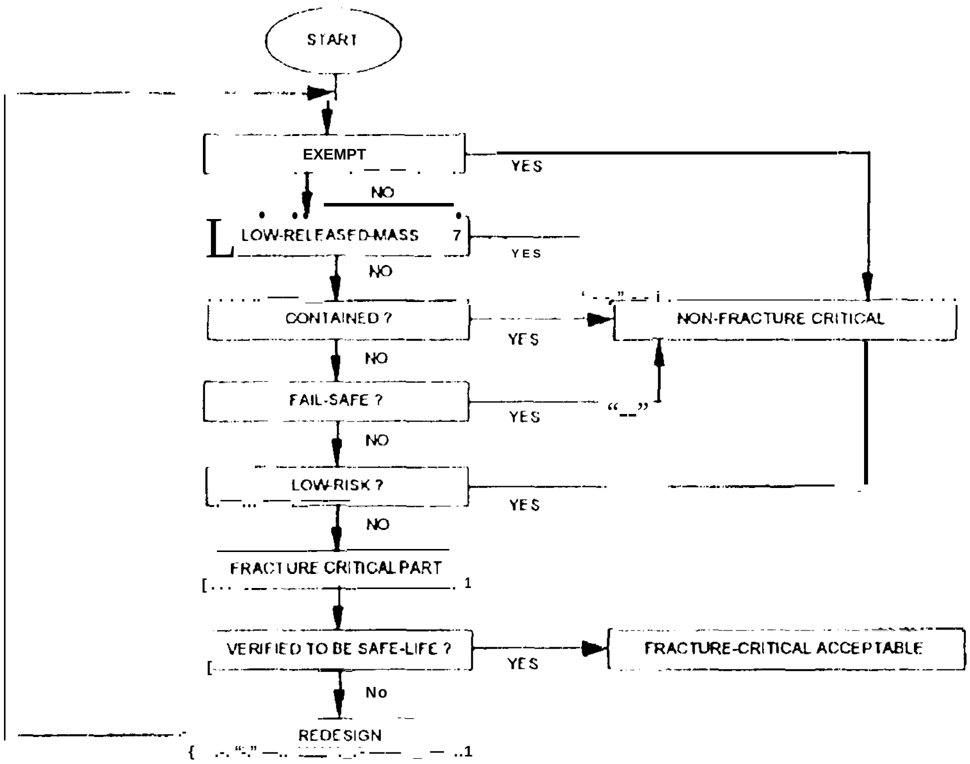

Figure 1 **Fracture Control Classification Process**

Table 1 **Minimum** Initial **Crack Sizes** for Fracture Analysis Based on NDE Method

U.S. CUSTOMARY UNITS (inches)

Crack Location	Part Thickness, t	Crack Type	Crack Dimension a	Crack Dimension c
		Eddy Current NDE		
Open Surface	t ≤ 0.050	Through	t	0.050
	t >0.050	PTC 1	0.020	0'100
			0.050	0.0s0
Edge or Hole	[≤ 0.075	Through	t	0.100
	t >0.075	Corner	0.075	0.075
		Penetrant NDE		
Open Surface	t s 0.050	Through	t	0.100
	.050< t < .07s	Through	t	0.15-t
	t >0.075	PTC	0.02s	0.12s
			0.075	0.07s
Edge or Hole	t ≤ 0.100	Through	t	0.100
	t > 0.100	Comer.	0.100	0.100
		Magnetic Particle NDE		
Open Surface	t ≤ 0.075	Through	t	0.12s
	[>0.075	PTc	0.03$	0.188
			0.075	0.12s
Edge or Hole	t <0.075	Through	t	0.2s0
	t >0.07s	Corner	0.075	0.2s0
		Radiographic NDE[3]		
open Surface	.025 ≤ t ≤ 0.107	PTC	0.7t	0.075
	I >0.107		o.7t	0.7t
		Ultrasonic NDE[2]		
Open Surface	t ≥ 0.100	PTC	0.030	0.150
			0.065	0.065

Notes:
1 - Partly Through Crack
2 - Sizes not applicable to very tight flaws (e.g., forging flaws or lack of full penetration in burl welds)
3.- Comparable to Class A quality level

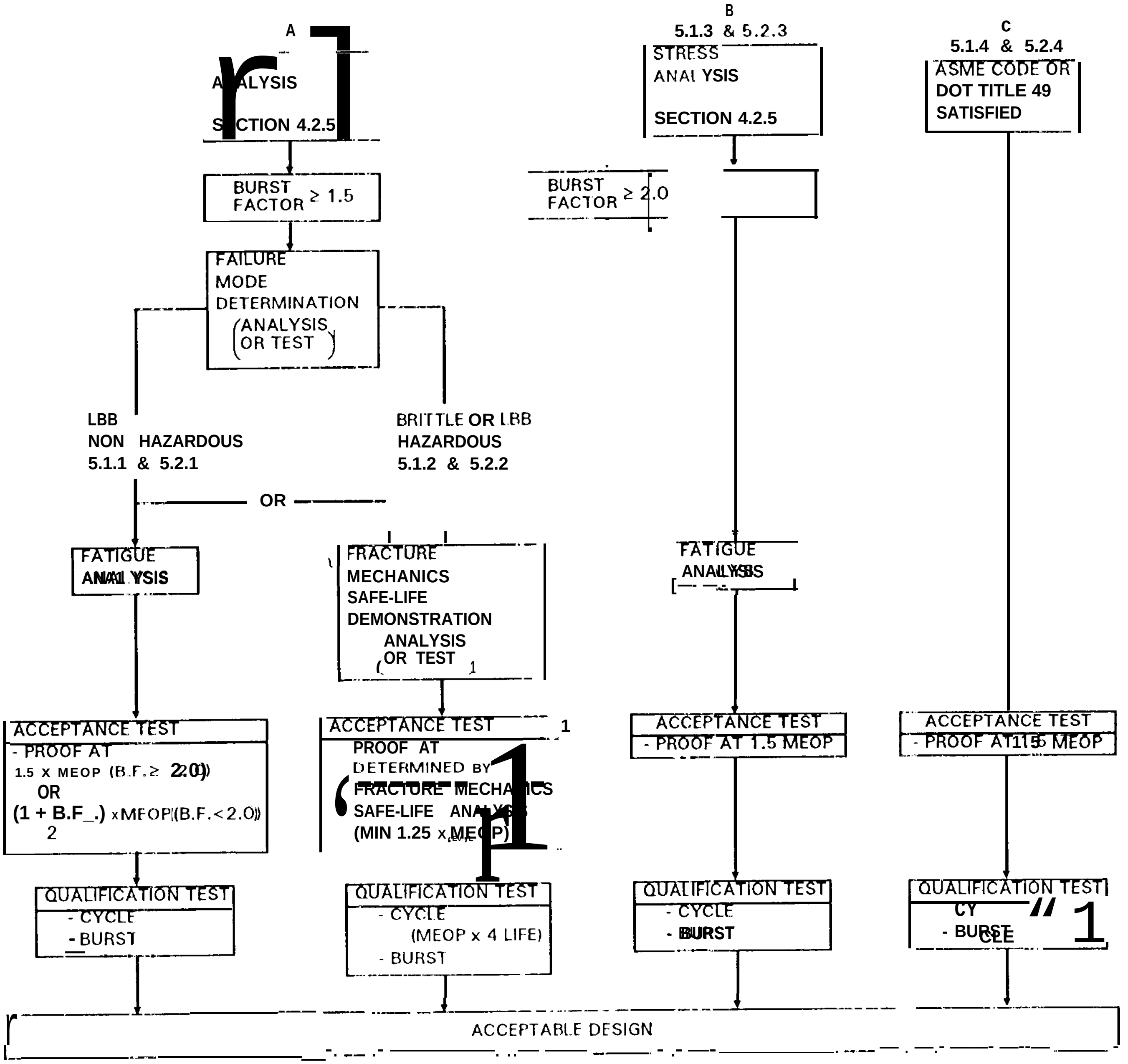

FIGURE 2 APPROACHES FOR DESIGN AND VERIFICATION OF PRESSURIZED COMPONENTS IN MIL-STD-1522A